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USING ITERATIVE ORTHOPHOTO REFINEMENTS TO CORRECT DIGITAL ELEVATION MODELS (DEM's)

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ABSTRACT

A new technique is described that can be used to correct the digital elevation data obtained using digital correlation methods on terrain stereoimages. The new technique takes advantage of the speed of modern computers and the inherent geometric relationship between elevation data and orthophotographs to provide a speedy, accurate and nearly automatic method for both generating and correcting digital elevation models (DEM's).

INTRODUCTION

Digital correlation methods provide a fast and effective means for automatically generating terrain elevation data from digital stereopairs of aerial photographs. Compilation rates of over two hundred points per second can be achieved on modern computers. The data produced have to be edited, however, and this can be a very tedious and time-consuming process. For example, the amount of correlation data produced in 15 minutes by the correlation method *match*, developed by the U.S. Army Topographic Engineering Center (TEC), can require up to 5 hours to inspect and edit using manual and computer-assisted techniques.

To minimize interactive editing requirements, TEC has developed a new DEM editing/generation technique named the "Iterative Orthophoto Refinements (IOR)" method. It is highly effective and is commensurate in speed with modern correlation methods. The IOR method, which is similar in concept to that reported by Schenk(1989), is based on the premise that, given a DEM and accurate exterior orientation parameters for a stereopair of digital images, it is possible to generate two, supposedly identical, orthophotos of the original stereoimages. If the orientation data are correct, any geometric mismatch between the two orthophotos will be caused by errors in the derived elevations. The mismatches can be measured automatically using a digital correlation method, converted to equivalent elevation errors and used to refine the original DEM. New orthophotos can then be generated from the updated DEM and the process repeated in an iterative manner until no measurable mismatches exist between the orthophotos.

A detailed description of the IOR method is given in the next section. This is followed by sections on test results, a discussion of the results and conclusions.

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THE IOR METHOD

The IOR method mainly requires the use of a digital correlation routine, a digital orthophoto generation capability and a technique for converting geometric mismatches between orthophoto pairs to equivalent DEM error. Each of these processes will be discussed in the following sections.

THE DIGITAL CORRELATION METHOD

The correlation method used in the IOR process is named *match*. It is the offspring of a program developed by TEC in the late 1970's named the "Digital Interactive Mapping Program (DIMP)." In the late 1980's, DIMP, which was written in the FORTRAN language for a CDC Cyber computer, was modified to include various new capabilities, rewritten in the C-language for a Silicon Graphics Iris 4D/85 engineering workstation and renamed *match*. A full description of *match* is beyond the scope of this paper. The reader is referred instead to Norvelle (1981) which describes DIMP in detail and is sufficiently applicable to *match*.

Match is an area-based digital correlation method that operates in image space and is referenced to an evenly spaced grid of points on the left image of a stereopair. That is, for equally spaced image points (grid) on the leftmate, *match* attempts to determine, based on the maximization of the normalized cross correlation coefficient, the image coordinates of corresponding points on the rightmate. This routine is used in two ways in the IOR method. First, correlation is performed on a stereopair of images to determine a dense grid of conjugate points. These points are intersected to obtain a DEM. The DEM is then used in conjunction with the exterior orientation data for the stereoimages to generate an orthophoto of each image of the stereopair.

Match is used in a second mode to automatically determine the geometric mismatches between the two orthophotos. The procedure is the same as in the first mode but now the conjugate image points determined by *match* should have identical orthophoto image coordinates. The extent to which they are not identical (mismatches) can be transformed into equivalent elevation errors that are then used to correct the current DEM values.

ORTHOPHOTO TRANSFORMATION

Orthophotos are produced using a differential rectification technique. Projection equations are used to rigorously compute corresponding image coordinates (xp,yp) for the ground coordinates (Xg,Yg,Zg) of a rectangular array of four DEM points. The Xg and Yg-ground coordinates of the DEM points are then mathematically related to their corresponding image coordinates according to Equations 1.

$$
\begin{aligned}
x_p &= a\,X_g + b\,Y_g + c\,X_g\,Y_g + d \\
y_p &= e\,X_g + f\,Y_g + g\,X_g\,Y_g + h
\end{aligned}
\qquad \text{Eqs (1)}
$$

Once the coefficients are determined, Equations 1 are used to compute image coordinates for ground points (orthophoto pixels) that fall within the boundaries of the four DEM values. For each computed image point (xp,yp), a gray level is extracted from the original image using bilinear interpolation and assigned to the orthophoto at coordinates Xg and Yg. The computations proceed from one rectangular array of DEM values to the next until the full orthophoto is generated.

The ground-sample value (meters) for each pixel of the orthophoto is selected by the user. Its value is normally chosen to have about the same ground resolution as a pixel on the input image. The orthophoto pixel size must also be divisible into the DEM spacing by some integer value. This is required so that the *match* routine will be capable of determining a mismatch between orthophotos at ground coordinates registered with the DEM values. For example, if an input image pixel is approximately equivalent to 2.12 meters on the ground, and the elevations in the DEM are spaced 25 meters apart, an orthophoto pixel will be chosen that has a 2.5 meter ground resolution. When *match* is used, conjugate points (mismatches) will be determined at a spacing of 25/2.5 = 10 pixels on the left orthophoto and will coincide exactly with a DEM value.

DEM ERROR COMPUTATION

Figure 1 shows the geometric relationship between mismatches in the orthophotos (dx) and the DEM error (dh) that caused the mismatch. P' is a measured DEM point (shown at the dot positions) and is in error by a value of dh. The orthophoto image of point P' falls at a ground position Xl on the left orthophoto and at Xr on the right. The mismatch between the two is dx. Since the coordinates of the camera stations and the ground positions of P'(Xl) and P" (Xr = Xl+dx) are known, it is possible to compute the position of P by intersection.

The error in elevation between P' and P can be computed and, if the slope of the true ground surface is known, converted to the error dh directly beneath the DEM point P'. The true ground slope is not known, however, but can be approximated from the measured DEM surface. Alternately, the approximate error, dh', can be computed as dh' = dx(H/B), where H/B is the reciprocal of the base-height ratio between camera stations. The error dh (or dh') can then be used to update the DEM value of point P'.

In cases where the DEM errors are erratic (individual "spikes" in the elevation data), the slope of the ground, as approximated by the slope of the DEM surface, may be in serious error. This will cause an exaggerated dh correction. In such cases, the approximate correction, dh', may be more dependable. In either case, since the true ground slope is not known, the IOR process is necessarily an iterative one.

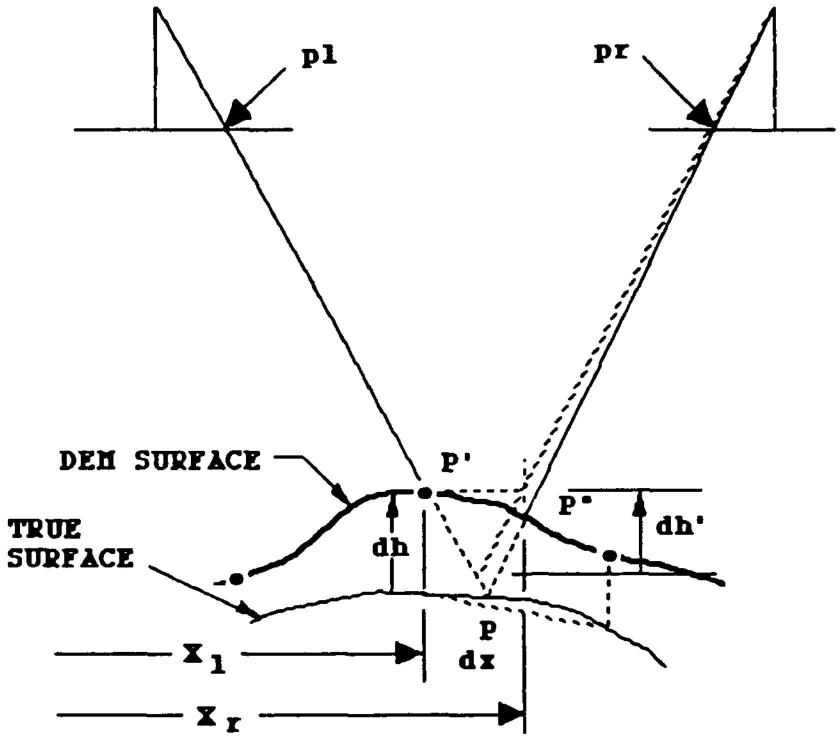


Figure 1. Relationship Between Orthophoto Mismatches and DEM Error.

RESULTS

TEST IMAGES

Two examples of test results obtained with the IOR method are given in this section. The first test was made with 1280 by 1024-pixel stereoimages obtained by scanning 1:40000 scale photographs of the San Bernardino Mountains in California (Figure 2a) with a 50-micrometer spot size. The terrain is very rugged (elevations range from 1350 to 1950 meters above sea level) with slopes up to 45 degrees and slope changes (ridges and valleys) approaching 70 degrees. Most valleys are lined with densely-populated, tall trees which were imaged with very little variance in gray shades. Ridge lines and slopes have a moderately-dense cover of small trees. The sharp slope changes and low radiometric variance in some image areas cause difficulties for a correlation method and large DEM errors will occur. These images, therefore, present a good test for the IOR method.

In the second test, 2048 by 2048-pixel stereoimages are used. They were obtained by scanning 1:20000 scale photographs of Fort Hunter Liggett, California, (Figure 2b) with a 25-micrometer spot size. The terrain is dotted with tall, isolated trees whose shadows are prevalent on one image but occluded by the trees themselves on the

other. The terrain, with elevations from 369 to 480 meters, is otherwise grass covered and provides very little radiometric variance in the images to support digital correlation and DEM generation. Large elevation errors can be expected, especially with regard to tree heights, making these images a difficult test of the IOR method.

(a) (b)

Figure 2. (a) San Bernardino Mountains *and (b)* Fort Hunter Liggett Test Images.

SAN BERNARDINO MTS TEST RESULTS

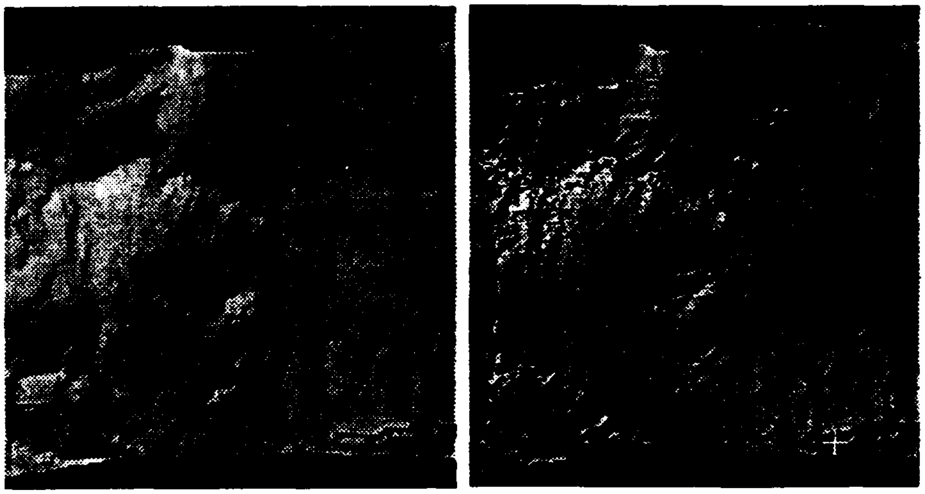
The original stereoimages were initially reduced in scale by 4x to (1) minimize the large x-parallaxes caused by the rugged terrain and (2) reduce the time required to obtain an initial DEM. The reduced images were correlated to provide a DEM with a 40-meter spacing. The spacing was changed to 10 meters by bilinear interpolation. The resulting DEM is shown as a shaded relief image in Figure 3a. The "sun" is in the upper-left corner at an altitude of 50 degrees from the nadir.

The initial DEM, although approximate, was used to generate a pair of orthophotos from the original, full-resolution stereoimages. The geometric mismatches (x-parallax) between the orthophotos were measured automatically with *match*, converted to elevations errors and used to refine the initial DEM. The mismatches equated to elevation errors ranging from -100 to +43 meters.

A second set of orthophotos were made and, when viewed in 3-D, were found to contain new, but smaller, mismatches. A second iteration of the IOR method was performed and detected elevation errors ranging in value from -11.0 to +13.6 meters. These errors were used to further refine the once-corrected DEM. The refined DEM is shown as a shaded relief image in Figure 3b. The total elapsed time for the above steps was 30 minutes.

For validation purposes, a third set of orthophotos were generated. No significant mismatches were found in the

new orthophotos except in one area of dense tree growth. The radiometric variance in this image area was so low that correlation was impossible. Any further DEM corrections would have to be made using manual editing techniques.



(a) (b)

Figure 3. San Bernardino Mtns. Shaded Relief Images of (a) The Approximate DEM and (b) The DEM After 2 Iterations of the IOR Method.

FORT HUNTER LIGGETT TEST RESULTS

Previous correlation experience with these images showed that it is nearly impossible for *match* to determine the conjugate images of the tall, individual trees because of the large x-parallax (16 pixels) between tree images and the adverse affects of large tree shadows. Consequently, the original stereoimages were reduced in scale by 4x to (1) reduce the large x-parallaxes, (2) reduce the size of tree shadows and (3) to minimize the time required to obtain an initial DEM.

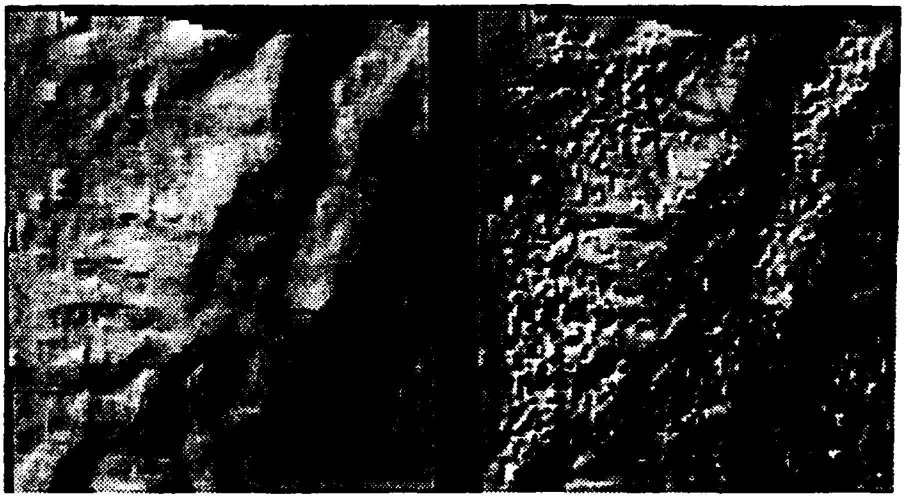
The reduced images were correlated at a 5-pixel spacing on the left image to create a DEM with a 10-meter spacing. This initial DEM is shown as a shaded relief image in Figure 4a. The "sun" is in the upper-left corner at an altitude of 65 degrees from the nadir.

Orhtophotos of the reduced images, with each pixel equal to a 2-meter ground-sample distance, were generated and viewed in 3-D to determine the efficacy of the initial DEM. Many significant mismatches were noted among tree images. Therefore, instead of immediately using full-scale orthophotos as in the test above, orthophotos of the reduced images were incorporated in the IOR process to further refine the DEM, including tree heights. Refinements were made for elevation errors that ranged in value from -11.6 to +9.0 meters.

Next, the original steroimages were reduced by 2x and used with the current DEM to create orthophoto pairs with each pixel equal to a 1-meter ground-sample distance. Four iterations of the IOR method were required to correct

the current DEM and produce acceptable orthophoto pairs. The ranges of detected elevation errors with each iteration of the IOR method were -6.9 to +11.1, -17.9 to +11.3 , -6.7 to +12.3 and -3.2 to +4.1 meters, respectively.

The previously corrected DEM was next used to create orthophotos of the original, full-resolution stereoimages. Each pixel of the orthophotos had a ground-sample distance of 0.5 meters. These orthophotos were correlated at every 20 pixels on the left orthophoto to register precisely with the 10-meter spacing of the DEM. After one iteration of the IOR method, elevation errors from -4.9 to +4.2 meters were detected and used to refine the current DEM. The IOR procedure was repeated a second time at full resolution and provided DEM corrections for elevation errors ranging from -2.0 to +2.0 meters. The resulting DEM is shown as a shaded relief image in Figure 4b.



(a) (b)

Figure 4. Shaded Relief Images of the Fort Hunter Liggett Test Area. (a) Initial DEM. (b) Final DEM.

Using the final version of the DEM, new orthophoto pairs were created and inspected in 3-D to validate that the DEM was correct. No mismatches were found in the terrain imagery but in some of the grass areas it was not possible to observe mismatches even if they existed. This is because there was not enough variance in the gray shades to provide adequate stereoviewing. Although the orthophotos may appear correct, the DEM may actually be in error.

Mismatches were still evident in the orthophotos where tall trees existed. This indicates that the true height of the trees had not been established by the IOR process. These trees are typically 12 meters in height and produce 16 pixels of x-parallax in the original stereoimages. The mismatches on the orthophoto pairs were generally 4 pixels in size (2 meters on the ground) which equates to an elevation error of about 3 meters.

DISCUSSION OF RESULTS

Figures 3 and 4 clearly illustrate that the IOR method is successful in adding high-resolution corrections to a DEM. The Figures do not show the accuracy of the corrections, however, but this is judged by 3-D viewing of the final orthophotos. The 3-D error surface, represented by mismatches in the orthophotos, should be flat. This, with some notable exceptions, was found to be the case in both tests.

SAN BERNARDINO MTNS TEST

The DEM of the San Bernardino Mountains was fully corrected except in one small area of the stereoimages. The image area is a very sharp, tree-lined valley. When generating the initial DEM, the abrupt change in slope direction, coupled with the low radiometric variance of the trees, caused the correlation process to fail and produce significant DEM errors in this region. Further DEM improvements by the IOR method were limited because, in the presence of adverse radiometric characteristics, the *match* routine could not accurately detect mismatches in the orthophotos. In adverse areas such as these, manual editing is required.

The IOR method was completed on the San Bernardino images in 30 minutes. In previous tests with these images, 5 hours were required to manually edit the data obtained by conventional correlation procedures on the full-resolution stereoimages. This is a 10 to 1 improvement in speed using the IOR method. Furthermore, orthophoto pairs made from the manually-edited DEM were not flat when viewed in 3-D, indicating that not all error had been sufficiently corrected.

FORT HUNTER LIGGETT TEST

The results of this test are considered to be very good in spite of the fact that the obtained tree heights are not totally accurate (± 3 meters). In previous tests, conventional correlation techniques were used on the full-resolution images and were not successful in detecting tree heights. The IOR method was successful because, by initially reducing the images and x-parallaxes by 4x, it was possible for *match* to correlate on individual trees and, consequently, obtain approximate tree heights. When orthophotos were generated, the positions of the tree tops were sufficiently corrected to allow the IOR process to detect mismatches and further refine the tree heights.

By stepping from 4x to 2x and finally to 1x-reduced images, it was possible to keep the x-parallaxes (mismatches) in the orthophotos small enough that they could be measured by *match* and corrected by the IOR process. If, as in the test above, the intermediate steps performed on the 2x-reduced images had been omitted, the mismatches at 1x would have been too large and the IOR method would have failed on these images.

GENERAL

In both test cases, the IOR method is considered more accurate and faster than conventional correlation on original stereoimages followed by manual or interactive editing. It is faster because the orthophotos are more nearly identical and less searching ("pull-in" range) is required to find the conjugate points. It is more accurate because dissimilarities between the original stereoimages, a potential cause of error in a correlation process, are essentially removed from the orthophotos.

Usually, two or three iterations are necessary to correct a DEM. Special cases, such as the Fort Hunter Liggett images, may require more. Generally, if the mismatches are not removed from the orthophotos in 3 iterations, conditions (occlusions,shadows,etc) probably exist which cause DEM errors that can only be corrected by manual methods.

CONCLUSIONS

- The IOR Method is a fast and effective technique for generating and editing DEM's.

- The orthophoto transformation process removes image dissimilarities and allows correlation on the orthophotos to be performed more accurately and faster than on the original stereoimages.

- Two to three iterations of the IOR method are typical for accurate DEM correction.

- The IOR method can be 10 times faster than manual editing methods.

ACKNOWLEDGEMENTS

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